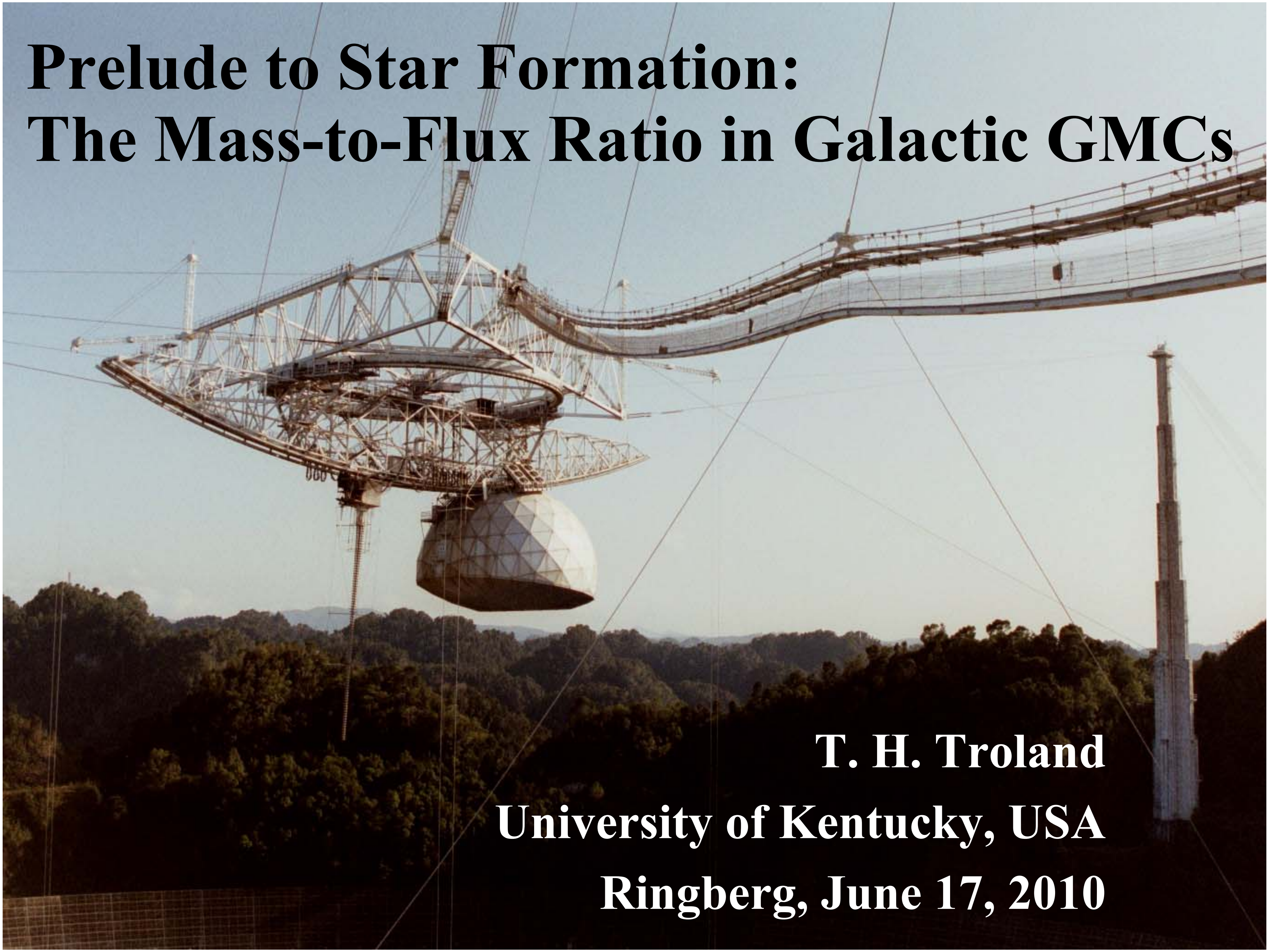
Prelude to Star Formation: The Mass-to-Flux Ratio in Galactic GMCs



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Ringberg, June 17, 2010

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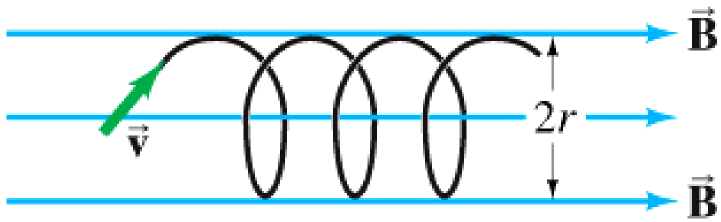
1. Magnetic Field Basics – Flux Freezing

- **Ions in the ISM directly coupled to magnetic field B_{ISM} via the *Lorentz force*.**



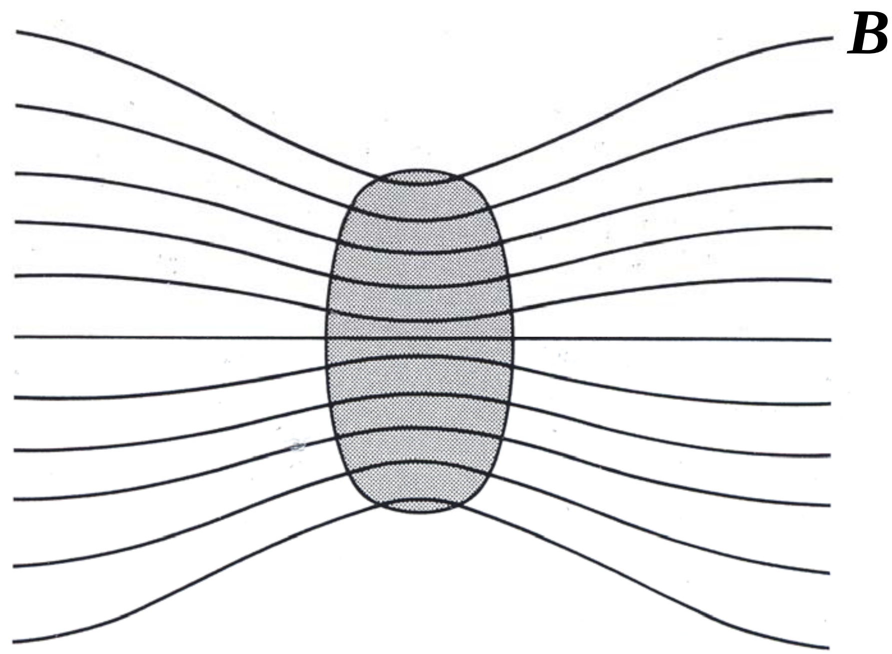
- **Neutrals coupled to ions via *ion-neutral collisions* as long as fractional ionization f_{ion} not too low[1].**

- **Coupling of ISM to B_{ISM} called *flux freezing***

[1]Starlight ionization of C atoms is sufficient to maintain good coupling

1. Magnetic Field Basics – Flux Freezing

- **Effects of flux freezing – B_{ISM} supplies support to self-gravitating cloud (in addition to internal motions)**



Shu, *The Physical Universe* (1982)

2. Magnetic Field Basics – Mass-to-flux ratio

- **If *B* is strong enough, it can *prevent gravitational collapse*.**

How strong is strong enough?

- **Set magnetic energy ≈ gravitational energy**

$$\pi R^3 \left(\frac{B^2}{8\pi} \right) \approx \frac{GM^2}{R}$$

(to within factors ≈ 1)

2. Magnetic Field Basics – Mass-to-flux ratio

- **Since magnetic flux $\Phi \approx \pi R^2 B$, this relation reduces by simple algebra to**

$$\left(\frac{M}{\Phi}\right)_{crit} \approx \left(\frac{1}{8\pi G}\right)^{1/2}$$

- **This is the *critical mass-to-flux ratio* $(M/\Phi)_{\mathrm{crit}}$.**

2. Magnetic Field Basics – Mass-to-flux ratio

- λ **parameter* defined as follows:**

$$\lambda \equiv \frac{(M/\Phi)}{(M/\Phi)_{critical}}$$

- $\lambda > 1$ **magnetically** ***supercritical***
- $\lambda < 1$ **magnetically** ***subcritical***

***Sometimes called** μ

2. Magnetic Field Basics – Mass-to-flux ratio

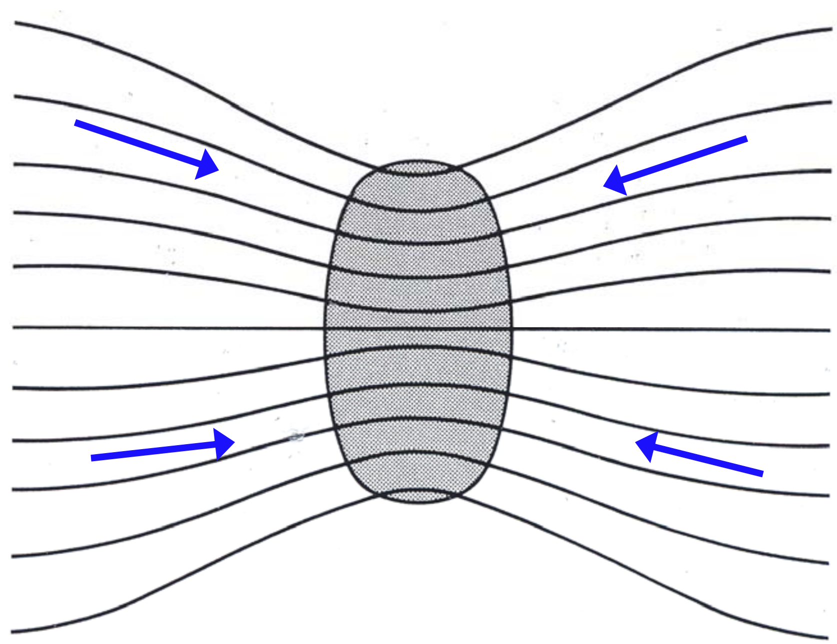
- **$\lambda > 1$ (*magnetically supercritical*)**
  - Gravitational energy > magnetic energy
  - Self-gravitating cloud *cannot* be supported by *B alone*.

- **$\lambda < 1$ (*magnetically subcritical*)**
  - Magnetic energy > gravitational energy
  - *B* supports the cloud *regardless of external pressure*.

recall $$\lambda \equiv \frac{(M/\Phi)}{(M/\Phi)_{critical}}$$

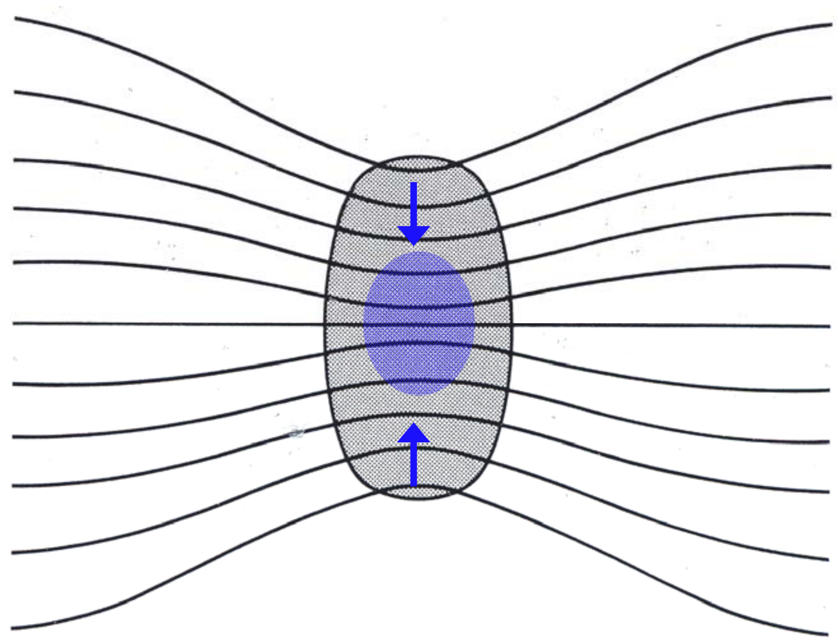
2. Magnetic Field Basics – Mass-to-flux ratio

- **λ can *increase* if**
  - External mass accumulates onto cloud along field lines



2. Magnetic Field Basics – Mass-to-flux ratio

- λ **can *increase* if**
  - Neutrals diffuse gravitationally through ions toward center of cloud - ***ambipolar diffusion********.



***High A_v in cloud core suppresses starlight ionization, reduces f_{ion}.**

2. Magnetic Field Basics – Mass-to-flux ratio

- **A theoretical argument – Self-gravitating clouds should be mildly magnetically *supercritcal* (e.g. McKee & Ostriker 2007)**

  – If gravity strong enough to overcome both *B* (turbulent & ordered) *and* internal motions, gravity should be stronger than *B* alone.

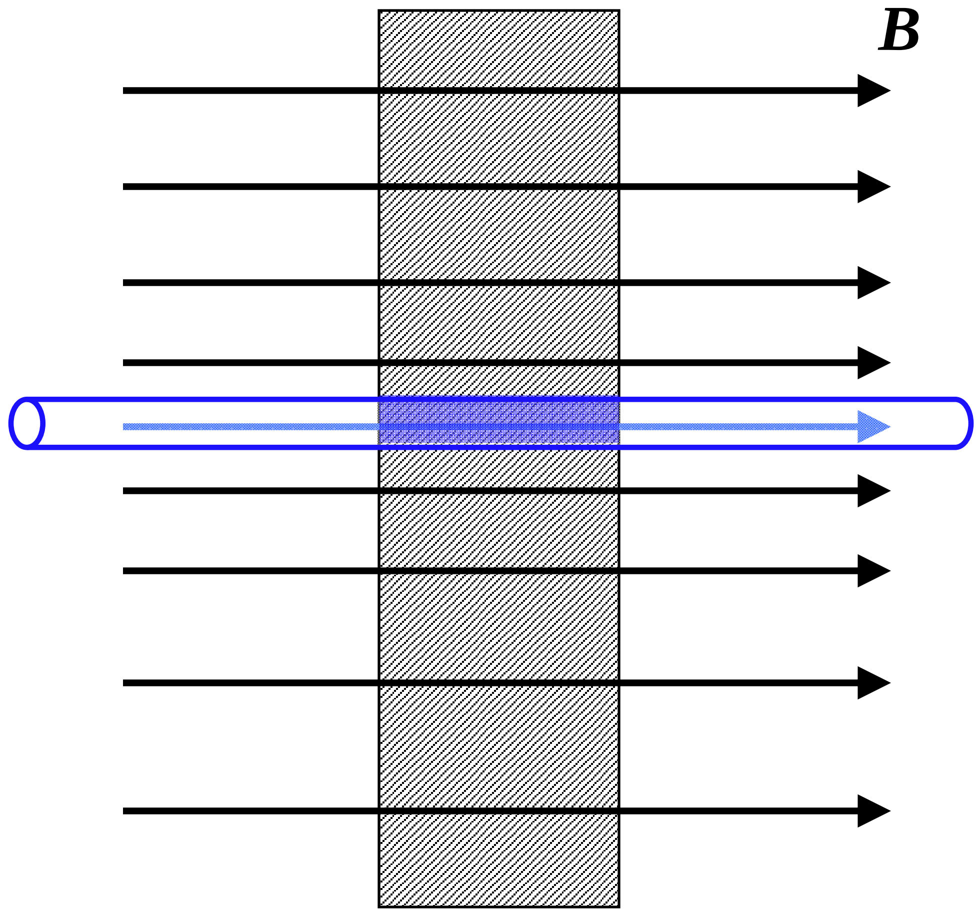
2. Magnetic Field Basics – Mass-to-flux ratio

- **How to measure M/Φ :**

  $N \propto M$ / unit area

  $B = \Phi$ / unit area

- **So** $(M/\Phi) \propto N/B$



2. Magnetic Field Basics – Mass-to-flux ratio

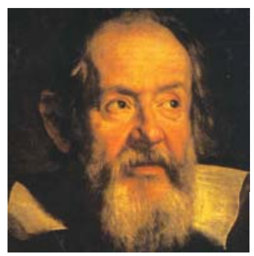
- **Observationally**

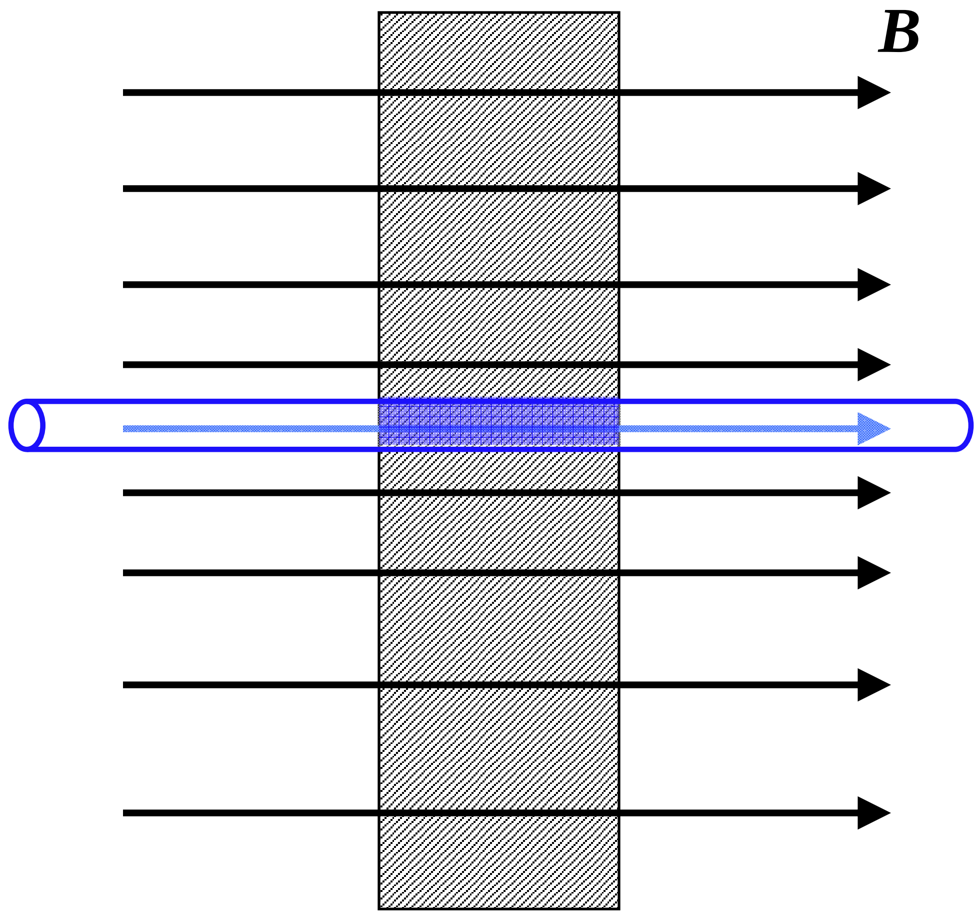
$$\lambda \equiv \frac{(M/\Phi)}{(M/\Phi)_{critical}} \approx 5.0 \times 10^{-21} \frac{N(H)}{B} \qquad \frac{cm^{-2}}{\mu G}$$

where *N(H)* is the *proton* column density

2. Magnetic Field Basics – Mass-to-flux ratio

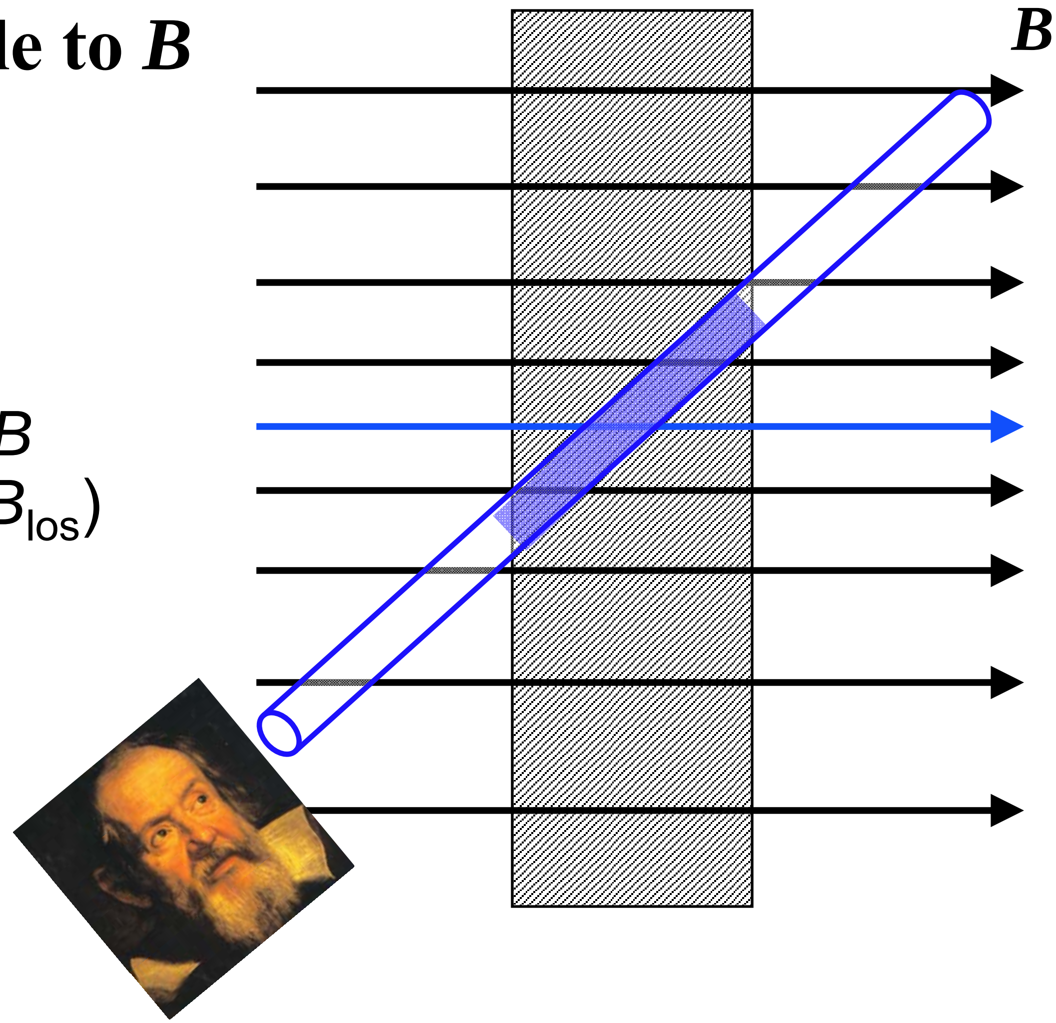
- **To measure true λ, we should observe along *magnetic axis*.**





2. Magnetic Field Basics – Mass-to-flux ratio

- **Observing at an angle to *B***
  - May *overestimate N*
  - May *underestimate B* (since we measure B_{los})
  - So we *overestimate* $\lambda \propto N/B$



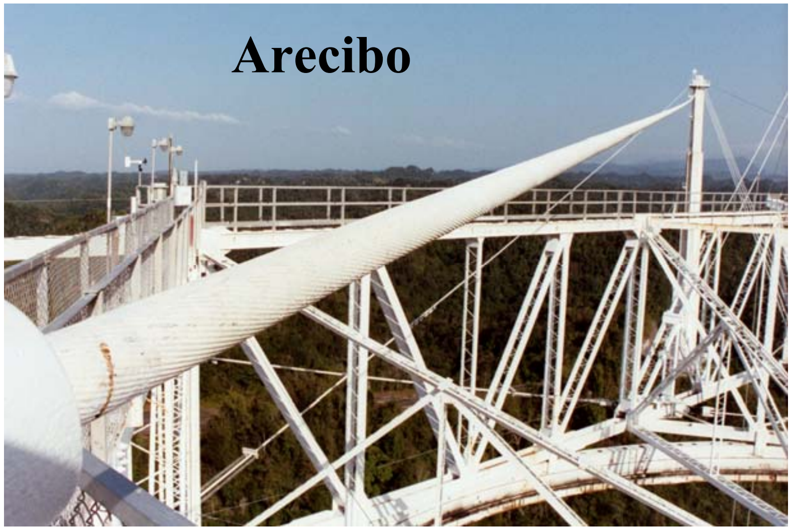
3. The Zeeman effect

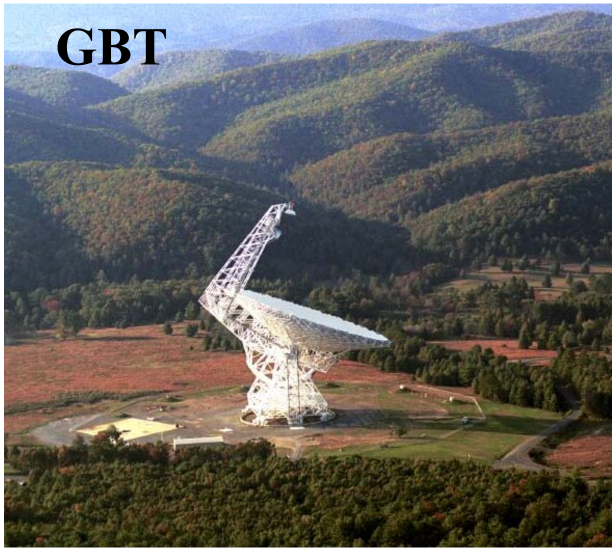
- **Radio frequency Zeeman effect is only technique that measures field strengths directly in *localized regions of ISM*.**

- **Limitations**
  - Only feasible for spectral lines from atoms or molecules with *unpaired electrons* (e.g. H^0, OH, CN).
  - Yields *line-of-sight* magnetic field B_{los} only, *not* total *B*
  - Requires very high sensitivity (long integration times)

4. Existing measurements of λ

- B_{los} **measured via Zeeman effect in two regimes:**
  - Diffuse HI gas (CNM) - via 21 cm HI Zeeman effect
  - Molecular cores - via 18 cm OH & 2.8 mm CN Zeeman effect



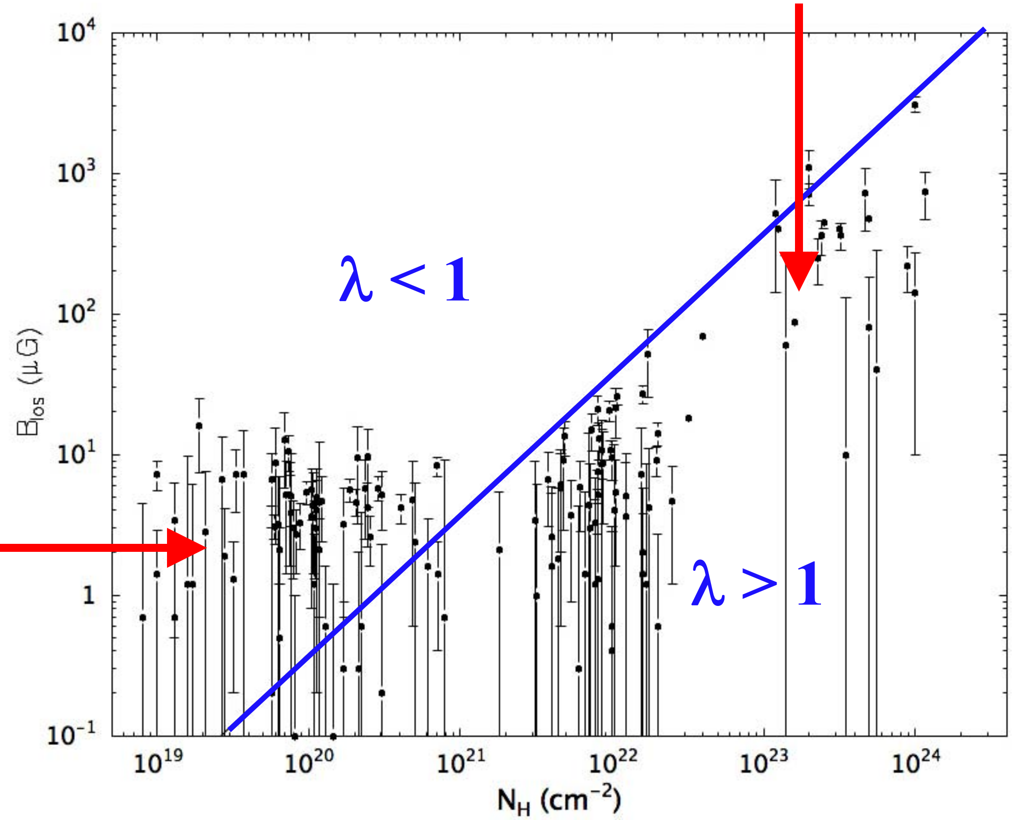


4. Existing measurements of λ

- ***N(H)*** **estimated from Zeeman-sensitive spectral line.**

- **For OH & CN Zeeman effects, one must adopt values for OH/H_2 and CN/H_2.**

Molecular cores (*supercritical*)



Diffuse HI gas (CNM)
subcritical

5. Importance of λ in GMCs

- **Most of volume of GMCs filled with low density gas ($n \approx 10^2$ cm^{-3}).**

- **No existing Zeeman measurements sample general lines-of-sight through GMCs (i.e. not through cores).**

- **So we do not know observationally if GMCs are magnetically sub or super critical *as a whole*.**

5. Importance of λ in GMCs

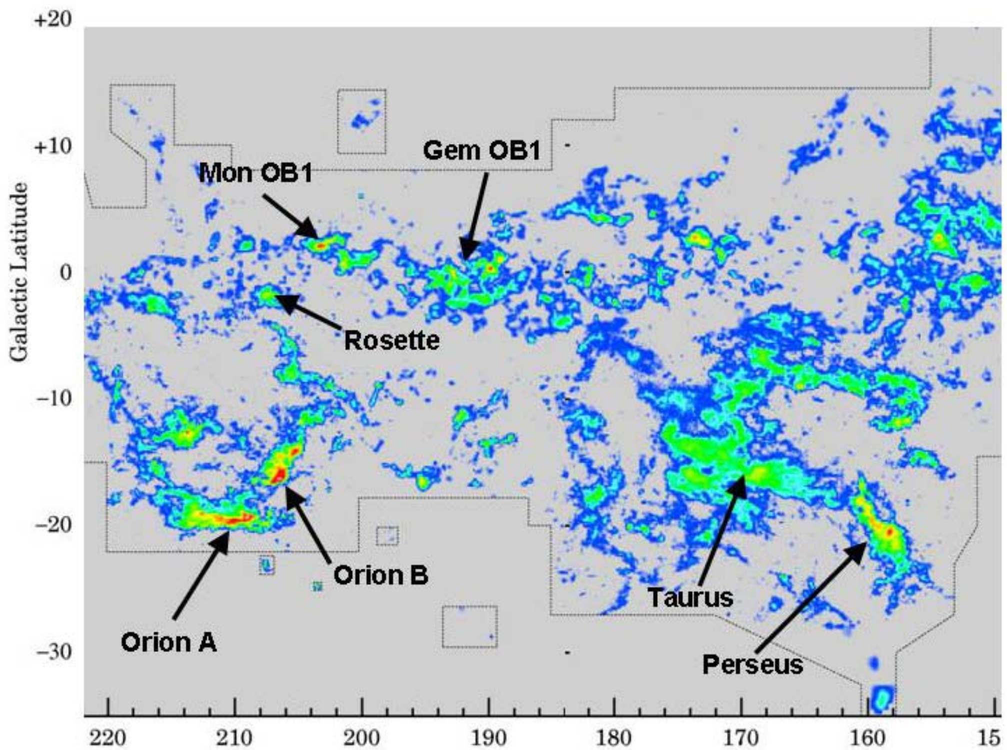
- **Theoretical arguments suggest GMCs are supercritical *if they are gravitationally bound*.**

- **However, GMCs may not be gravitationally bound if there were formed by (e.g.) colliding flows.**

- **The only way to know λ_{GMC} – Zeeman effect observations**

5. Importance of λ in GMCs

- **For a typical GMC:**
  - $N(\mathrm{H}) \approx 1.5 \times 10^{22}$ cm^{-2} (corresponds to Av ≈ 6)
  - If $\lambda = 1$, then $B_{tot} \approx 75$ μG.



^{12}CO (Dame et al. 2001)

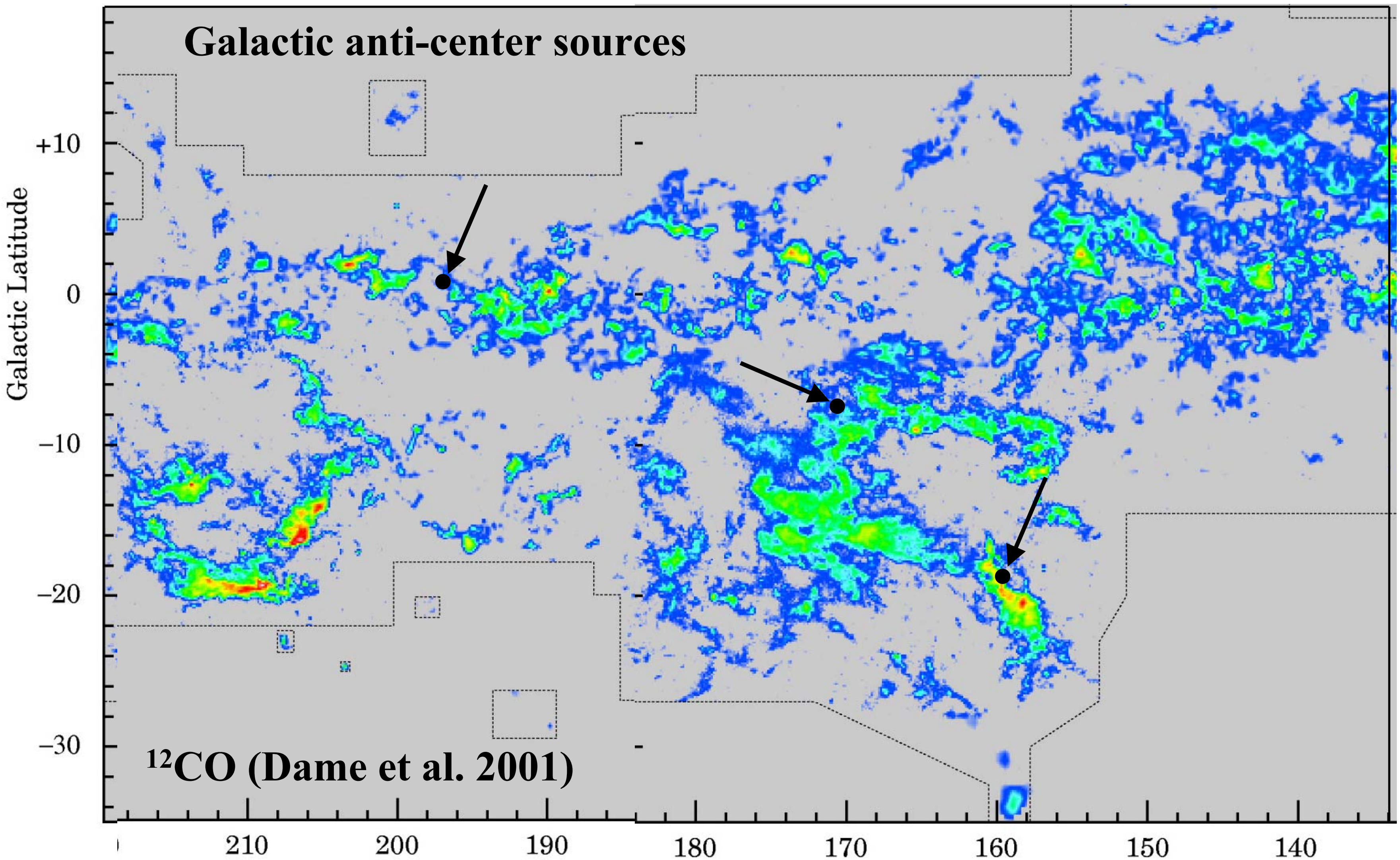
6. The Arecibo GMC Zeeman Project

- **Choose extra-galactic continuum sources behind galactic GMCs**
- **Search for Zeeman effect in 18 cm (1665, 1667 MHz) *OH absorption lines* towards these sources.**
- **Lines-of-sight sample GMCs *as a whole*, not just molecular cores.**

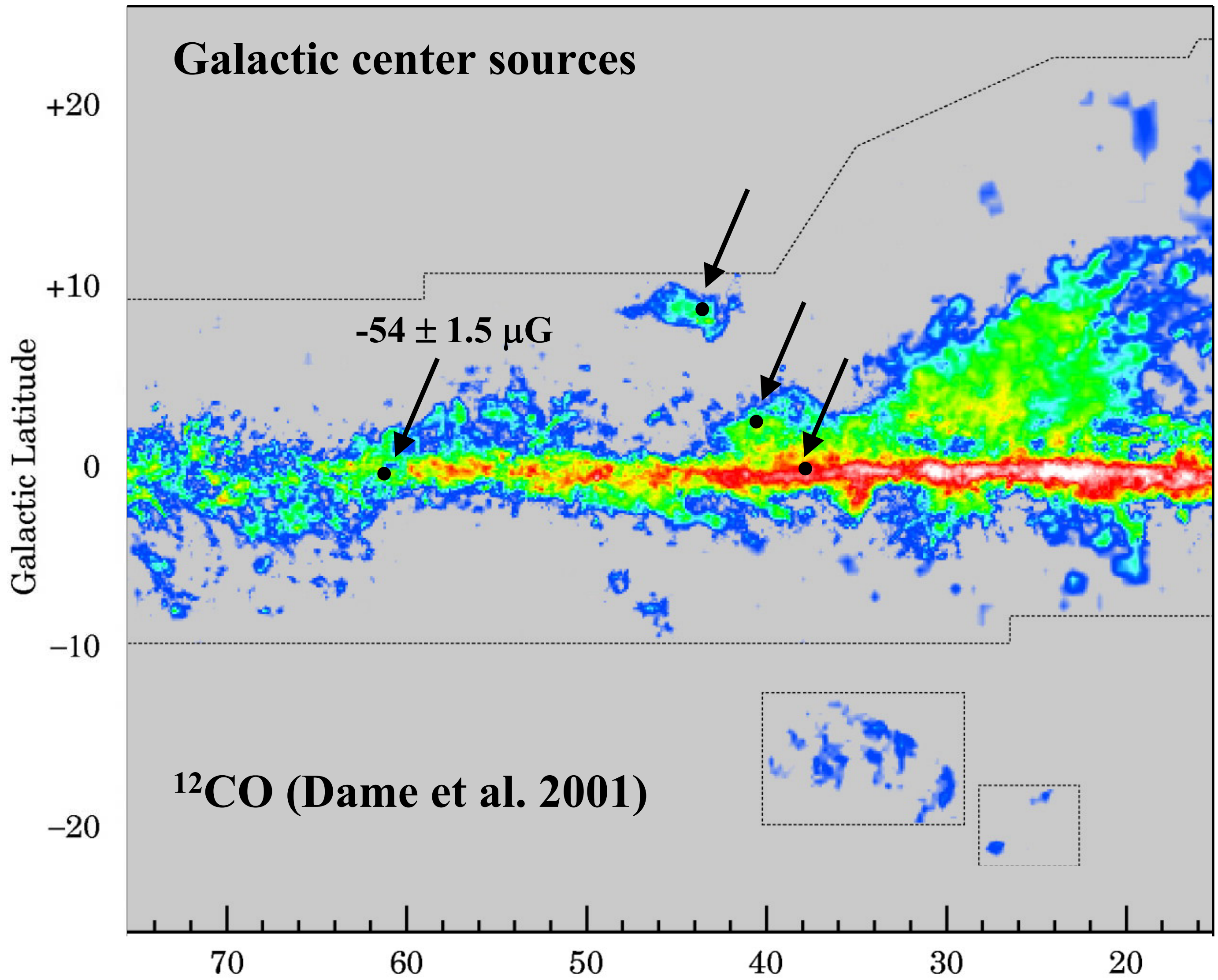
6. The Arecibo GMC Zeeman Project

- **After 80 hours of integration time (so far) we have observed OH absorption toward:**
  - 4 sources in galactic center region ($l \approx 30\text{-}70^{o}$)
  - 3 sources in galactic anti-center region ($l \approx 160\text{-}200^{o}$)
- **Between 2 and 20 hours of integration time per source**

6. The Arecibo GMC Zeeman Project



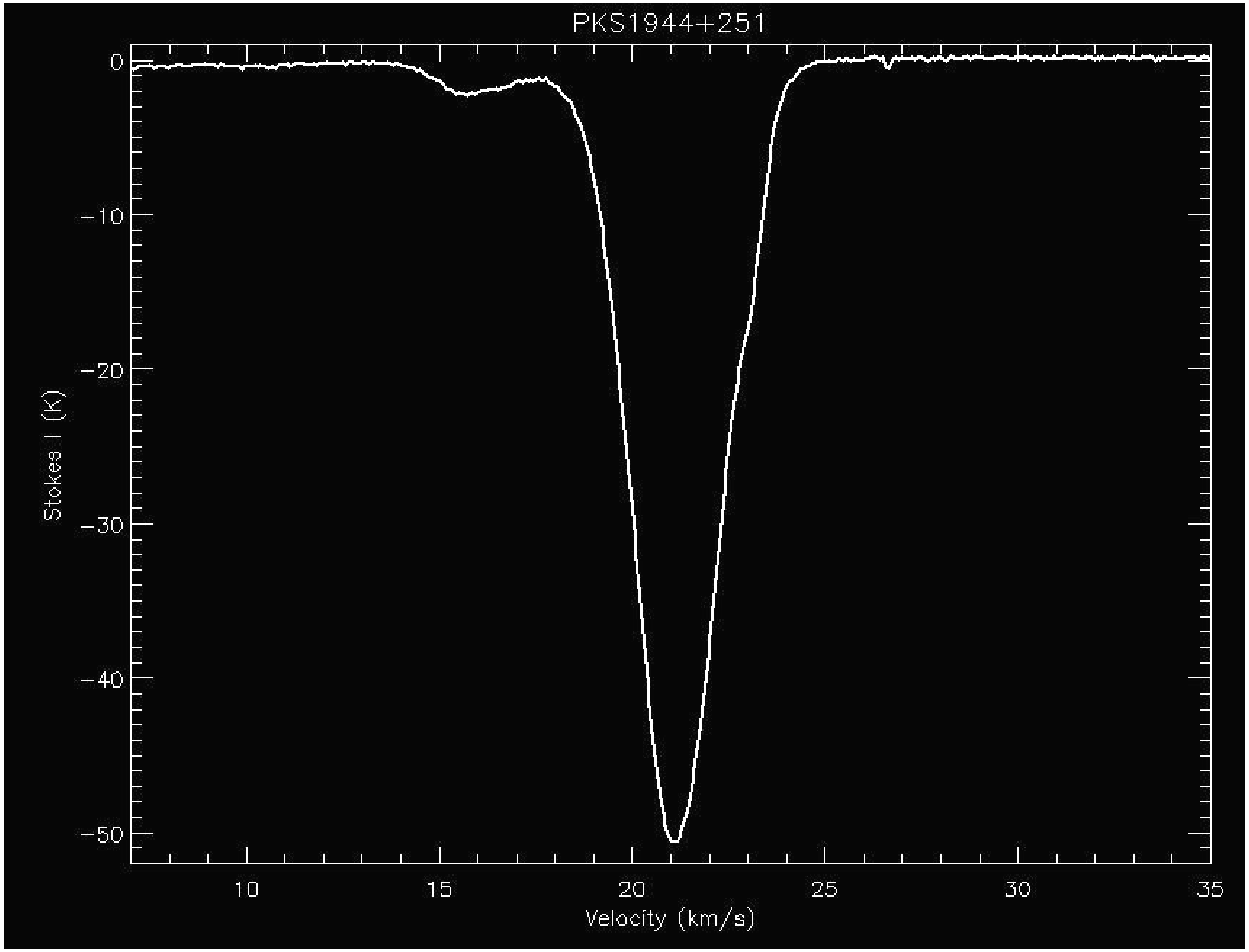
6. The Arecibo GMC Zeeman Project



6. The Arecibo GMC Zeeman Project

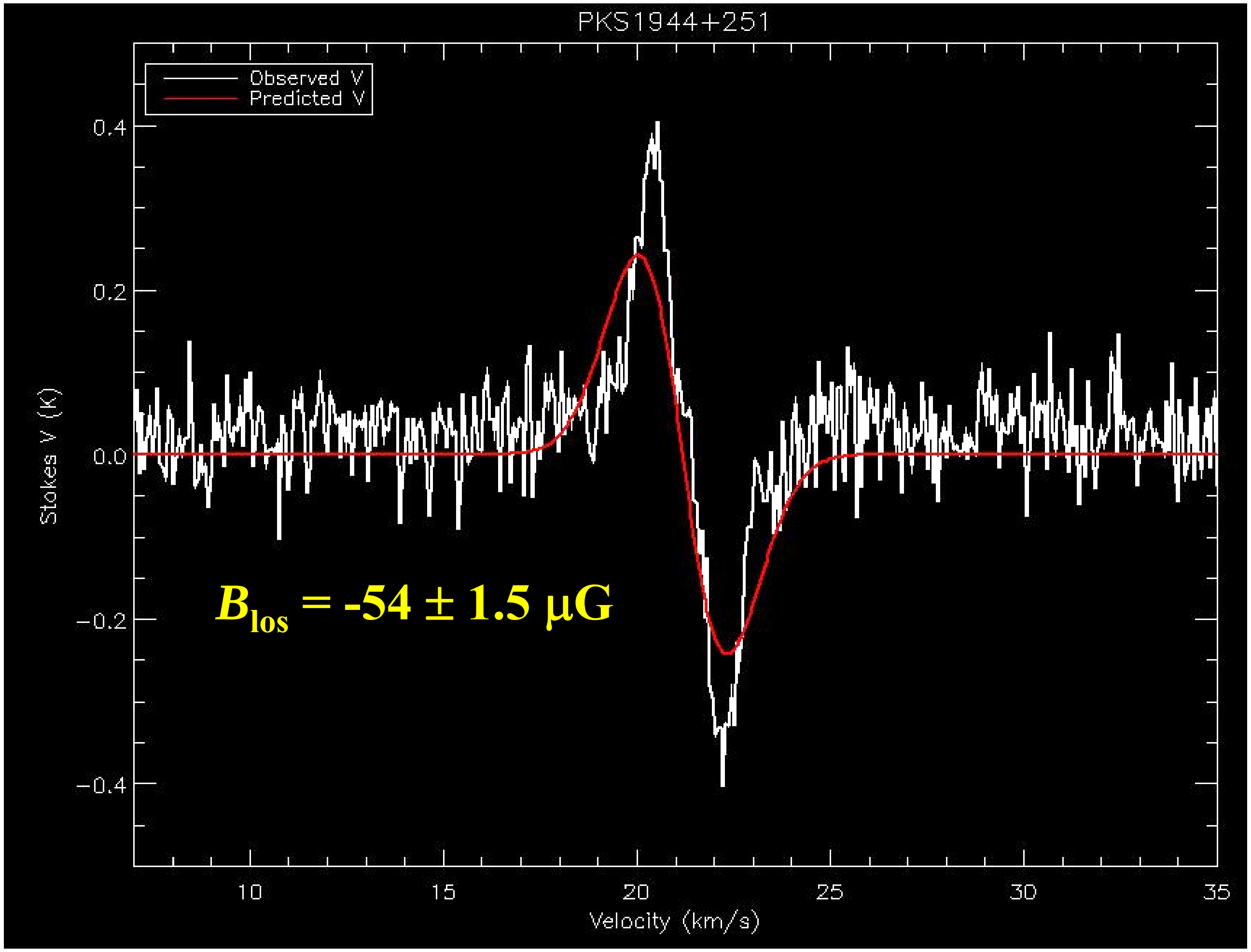
- **PKS 1944+251 – Stokes *I* (RH + LH circular pols)**

1667 MHz line



6. The Arecibo GMC Zeeman Project

- **PKS 1944+251 – Stokes *V* (RH – LH circular pols)**



1667 MHz OH line

6. The Arecibo GMC Zeeman Project

- **Table of *preliminary* results (anti-center sources)**

Source	l	b	$N(H_2)$	B_{los} μG	$\sigma(B_{los})$	λ
3C092	159.7	-18.4	1.0×10^{22}	15	13	7
3C131	171.4	-7.8	5.2×10^{21}	0.9	4.9	57
4C+14.18	197.0	1.10	1.8×10^{21}	1.1	9.0	17

6. The Arecibo GMC Zeeman Project

- **Table of *preliminary* results (galactic center sources)**

Source	*l*	*b*	$N(H_2)$	B_{los} μG	$\sigma(B_{los})$	λ
4C+13.67	43.5	9.2	4.3×10^{21}	-23	31	2*
B1853+0749	40.5	2.5	2.1×10^{22}	-16	9.8	13
			6.9×10^{22}	-13	5.6	52
			5.1×10^{21}	-8.5	7.8	6

*Short (2 hour) integration time

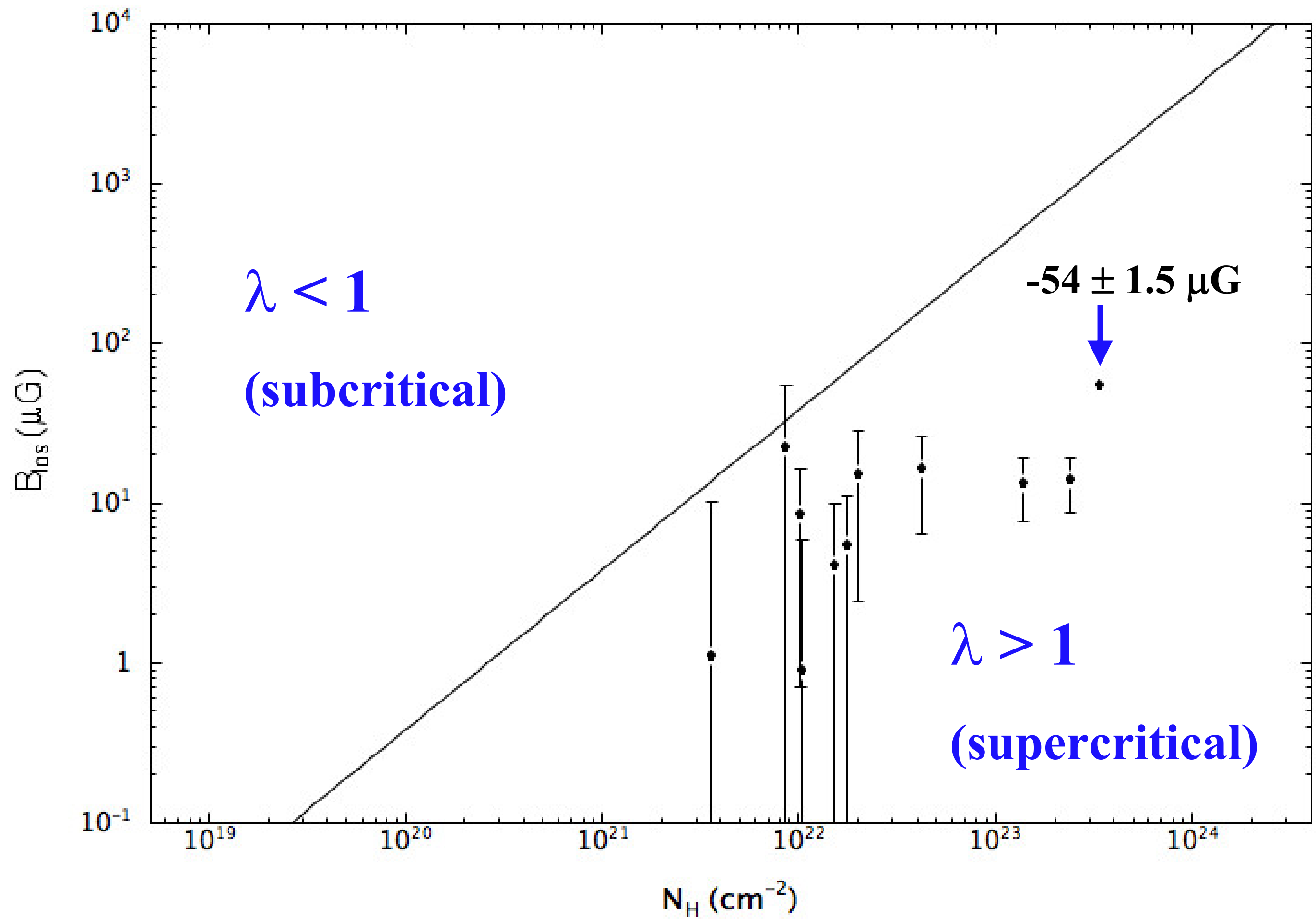
6. The Arecibo GMC Zeeman Project

- **Table of *preliminary* results (galactic center sources)**

Source	*l*	*b*	$N(H_2)$	B_{los} μG	$\sigma(B_{los})$	λ
B1858+0407	37.8	-0.2	1.2×10^{23}	14	5.2	85
			7.6×10^{21}	4.1	5.7	18
			8.8×10^{21}	-5.4	6.6	16
PKS1944 +251	61.5	0.1	1.7×10^{23}	-54	1.5	31

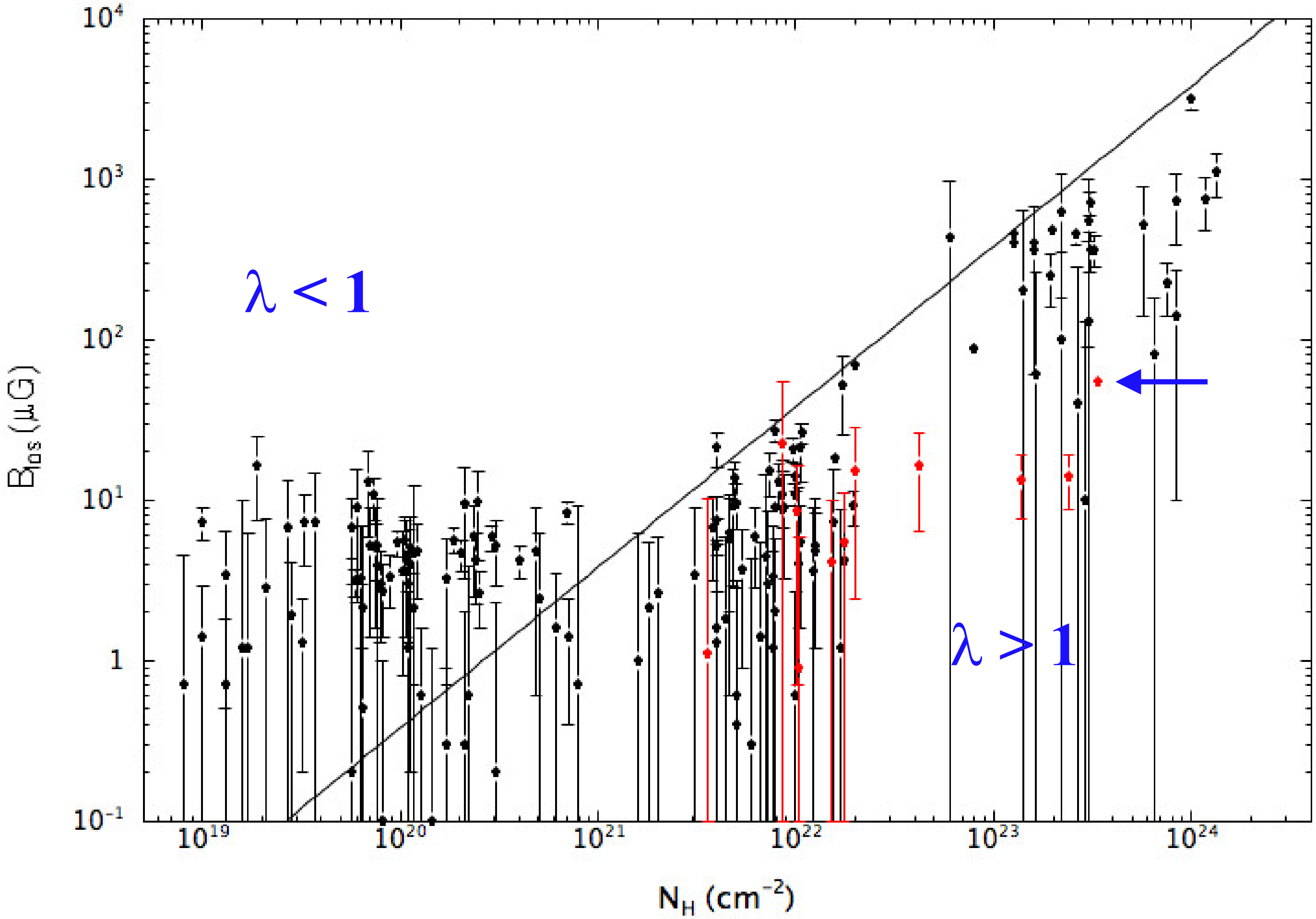
6. The Arecibo GMC Zeeman Project

- **New results from Arecibo GMC project**



6. The Arecibo GMC Zeeman Project

- **All results (new results in red)**



6. The Arecibo GMC Zeeman Project

- **Significance – GMCs appear to be *magnetically supercritical* ($\lambda >> 1$)**

- **However λ may be smaller if**

  – T_{ex} (OH) *smaller* than assumed 30 K

  – N(OH) / $N(H_2)$ *larger* than the value for dark clouds

  – $B_{tot} >> B_{los}$ (i.e. unfavorable geometry for Zeeman effect)